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Review

State of the art review and future directions in oil spill modeling

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ABSTRACT

A review of the state of the art in oil spill modeling, focused on the period from 2000 to present is provided. The review begins with an overview of the current structure of spill models and some lessons learned from model development and application and then provides guiding principles that govern the development of the current generation of spill models. A review of the basic structure of spill models, and new developments in specific transport and fate processes; including surface and subsurface transport, spreading, evaporation, dissolution, entrainment and oil droplet size distributions, emulsification, degradation, and sediment oil interaction are presented. The paper concludes with thoughts on future directions in the field with a primary focus on advancements in handling interactions between Lagrangian elements.

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1. Introduction

State of the art reviews of oil spill models have been performed approximately every 5 to 10 yrs. over the past two decades providing insight into the evolution of spill models and their use in supporting spill response and impact assessment (Huang, 1983; Spaulding, 1988; ASCE, 1996; Reed et al., 1999; NRC, 2003; Afenyo et al., 2015). Recently Spaulding et al. (2012) have performed a review to support the development of the next generation of spill model for the US Bureau of Ocean Energy Management (BOEM). NOAA has also undertaken a review and is developing the next version of General NOAA Operational Modeling Environment/Automated Data Inquiry for Oil Spills (GNOME/ADIOS) in support of spill response. The field has matured to the extent that textbooks are beginning to emerge on Lagrangian modeling techniques that include applications to oil spills (Lynch et al., 2015).

The objective of the present paper is to provide a brief review of the current state of development of oil spill models and a sense of future directions. The review focuses on some highlights of recent developments but is not comprehensive given space limitation. The review begins with an overview of the fundamental structure of spill models (Section 2) and lessons learned in the development and application of models over the past decade (Section 3). A review of transport and fate processes included in the models is provided in Section 4. Future directions in spill modeling are provided in Section 5, Conclusions and Summary in Section 6, and references in Section 7. The review mentions modifications to address oil ice interactions and modeling of blowouts but does not provide a review in these areas. The reader interested in modeling of blowouts might wish to review the results of an inter-comparison study of the most recent generation of blowout models performed on behalf of the American Petroleum Institute (API), through the Joint Industry Task Force, D3 Subsea Dispersant Injection Modeling Team for a selected series of test cases and summarized in Socolofsky et al. (2015).

2. Structure of current generation of oil spill models

A review of the current generation of spill models (Oil Spill Contingency and. Response Model or OSCAR (Reed et al., 2000), Spill Impact Model Application Package/Oil Modeling Application Package or SIMAP/OILMAP (French McCay et al., 2015; Spaulding et al., 1992), GNOME/ADIOS (Lehr et al., 1992, 2000, and 2002; Zelenke et al., 2012a, 2012b), and others) shows that the basic structure is essentially formulated using Lagrangian based methods (Lynch et al., 2015) for the transport processes (advection and dispersion) and individual algorithms for the fate processes. All models address the three dimensional surface and subsurface transport and fate processes and can be applied to both surface and subsurface releases. The current generation of spill models uses the random walk method, the lowest level of the hierarchy of Lagrangian methods (Spaulding et al., 2006; Lynch et al., 2015), for predicting transport. The wind, wave and currents necessary as input are provided by supporting environmental (hydrodynamic, wind, and wave) models. The hydrodynamic models maybe either 2 or 3 dimensional, while the wind and wave models are typically two dimensional, focusing on surface transport processes. As an alternative, information for ocean currents may come from broad scale measurement systems, such as high frequency radar (HFR) or data-based methods, and winds from offshore buoys. If the oil is at the surface, it is treated as a series of Lagrangian elements (LE), each of which is tracked in space and time; and when the oil is tracked at the subsurface, the LEs are oil droplets tracked by droplet size class. The algorithms that describe the fate processes are typically based on underlying fundamental principles and informed/calibrated/validated by laboratory and field observations. The fate processes are modeled either by transferring oil mass between the environmental compartments (sea surface, atmosphere, water column, sea bed, and shoreline) or changing the oil's composition or physical characteristics (e.g. density, viscosity, and interfacial tension). In many cases, the algorithms are empirically based, and hence rely on laboratory or field observations, therefore with the inherent limitation given the lack of availability of this type of information for the wide variations in spill situations. The oil in spill models is either characterized as a bulk oil of a given type (e.g. medium crude, No 2 fuel oil, etc.), or described in terms of the various components, typically related to its distillation, that comprise the oil. The models track the location of the oil through the distribution of oil mass (total or by component) in space (at the sea surface and in the water column, but typically not in the atmosphere) and time. The component distribution is required for performing impact assessment, where oil composition is critical to dissolution and biodegradation and impact on marine life.

3. Lessons learned and guiding principles

Based on a review of the development and application of oil spill models for spill response, impact assessment, including model validation against every major oil spill in the world, some important lessons in the design of spill model have been learned. These include:

- Spill models are typically structured as an integrated series of algorithms describing individual fate and transport processes. It is best to have each fate process as a separate algorithm with supporting data provided from other algorithms as appropriate. There may be many potential algorithms for each fate process, and the model framework needs to accommodate this functionality and allow the use of various approaches.
- The model needs to explicitly incorporate quantification of the uncertainty in the algorithms and associated coefficients used in the model, with predictions not only representing the mean value but the uncertainty as well.
- Each algorithm in the model should be thoroughly documented and tested prior to integration into the overall model system. Rigorous attention must be paid to ensure that the oil mass balance is preserved in each algorithm and throughout the integrated model.
- It is critical to be able to represent the behavior for temporally and spatially dependent releases of oil. For example, in the case of the Deepwater Horizon oil spill the release was originally coming from the end of the collapsed riser, then from the collapsed riser and a series of holes at a kink in the riser, and after the riser cut from one location above the well head. The release rate, gas to oil ratio, and oil droplet size distribution at each location varied with time, over relatively short time scales (Spaulding et al., 2015, 2016a, 2016b).
- Spill models employ a three dimensional, Lagrangian-particle-based strategy to represent the oil. This allows the model to account for the temporally and spatially varying release, transport, and fate of the oil. This strategy is also amenable to sensitivity testing of results to the number of particles in the simulation. Care needs to be exercised in the particle tracking and aggregation/disaggregation routines, to ensure that the total oil mass and the mass by each component is preserved.
- For many applications the chemical characteristics of the oil (i.e., oil "weathering") needs to be tracked in order to reliably estimate the mass balance and concentrations of various components of the oil, both in particulate (oil droplet) and dissolved phases. This partitioning in the environment has important implications for the impacts of oil on the marine ecosystem.
- Model output, at a minimum, should include the oil mass balance and the spatial (surface and subsurface) and temporal distribution of the oil.
- A geographic information system (GIS) framework should be used since it provides an effective and efficient tool to visualize model

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